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Қ. И. Сәтпаев атындағы Қазақ ұлттық техникалық зерттеу университеті

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
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DEVELOPMENT OF MATHEMATICAL MODELS DESCRIBING THE PROCESSES OCCURRING IN THE RAILWAY TRACK CONSTRUCTION AS A WHOLE, OR IN THE WORK OF ITS INDIVIDUAL ELEMENTS

Abstract. The article presents the development of mathematical models describing the processes occurring in the construction of a railway track as a whole, or in the work of its individual elements, an example of calculating the stress-strain state of the soil of two-layer embankments filled from the soils of the South Kazakhstan.

Key words: ground, embankment, railway, roadbed, finite element model.

Introduction. When designing an earthen cloth in the traditional calculations of normal, tangential and principal stresses, it is conventionally assumed that the grounds under the influence of a temporary train load operate in an elastic stage. In this case, the calculations do not take into account the heterogeneity of the constituent embankments. In mathematical models of embankments, they are assumed to be isotropic.

Such design schemes and assumptions do not correspond to the actual load of the roadbed from the rolling stock. The top of the roadbed actually perceives the load from the ballast prism, which perceives the pressure of the sleeper sole. Behind the ends of sleepers, the top of the road bed is not loaded with a vertical train load [1-6].

As a consequence of this stresses distribution in the embankment body, in the initial period of railway embankments stabilization, longitudinal cracks running deep into the embankment, which are usually grounded by a uniform ground, can often be seen on their bumps.

In traditional calculations of the roadbed, the top track structure (rail type, sleepers, ballast prism sizes) and the earthen cloth shape (width of the main platform, steepness of the slopes, the presence of berms, etc.) are not taken into account, the characteristics of which significantly affect the distribution of the train load top of the roadbed and in the roadbed body.

In traditional calculations, the embankment sediments and the sediments of its base are considered as one-dimensional, although in fact deformations vary both along the path and the height of the embankment, that is, they are voluminous. Traditional calculations of the roadbed cannot calculate many modern ways of roadbed treating. The drawback of the traditional calculating method of the roadbed is the lack of a unified approach to assessing the mechanical properties of the roadbed. Thus, in calculating the embankments sediments and their bases, the ground is considered elastically deformable. When calculating the local and full stability of the embankment, it is considered that the ground is absolutely rigid. Also, different situations are possible, depending on the embankments arrangement from different types of grounds, which are not regulated by normative documents.

These drawbacks of the traditional calculations of the roadbed were due to the lack of computational computing systems and computing facilities (which are available today), as well as insufficient knowledge of the physical and mechanical (strength) properties of local grounds. It is obvious that with inaccurate initial data on the ground characteristics, precise numerical methods of calculations are inexpedient.

Thus, the article considers:

- improvement of the installation for ground testing on shear in order to determine reliable initial data, taking into account the influence of vibrodynamic and pulsating loads on the strength and deformation parameters of clay grounds of various types;
- development of mathematical models describing the processes occurring in the construction of the railway track as a whole, or in the work of its individual elements;
- an example of calculating the stress-strain state of groung of two-layer embankments spilled from the soils of the Southern region of Kazakhstan

A great contribution to the study of the stress-strain state under the train load, using detailed virtual prototypes of railway embankments, was made by the professor [5-13].

Theory of the question. Finite element models of railway embankments. When considering a rigid body as an undeformable (absolutely solid), it is described by its mass $m = \iiint \rho d\nu$, the moment of inertia with respect to an arbitrary axis $\vec{r}_0$ $I_{\vec{r}_0} = \iiint \rho[\vec{r},\vec{r}_0]^2 d\nu$, the position of the center of inertia $\vec{r}_{(i.c.)} = \iiint \rho\vec{r} d\nu$, and the orientation $\vec{\varphi}$. All inertia moments of the body can be expressed through three moments of inertia relative to the main mutually perpendicular axes (passing through the center of inertia). The moment of inertia about an axis that does not pass through the center of inertia, located at a distance R from it, can be recalculated: $I = I_{(i.c.)} + R^2 \iiint \rho d\nu$. For a body of constant cross section, the moment of inertia of the section relative to the axis perpendicular to it can be introduced: $I_{\vec{r}_0(sec)} = \iint \rho[\vec{r},\vec{r}_0]^2 ds$.

Deformations of a rigid body can be described by a displacement vector $\vec{u} = \vec{r}_{deformed} - \vec{r}$ of each point $\vec{r}$ of a solid body, but this description is convenient only for describing the change in the position of the entire body, but not its deformations. It is used to describe the motion of an undeformed body, since for this it is necessary to consider only the position of the center of mass and the orientation of the body ($\vec{r}_{(i.c)}$ and $\vec{\varphi}$).

To describe the deformations of a rigid body and the resulting stresses, such a method requires the introduction of additional quantities characterizing the relative displacements of the points of the solid body. Such a value is the strain tensor $\hat{\varepsilon}$, which is introduced by means of the expression: $(d_{\vec{r}_{deformed}})^2 - (d\vec{r})^2 = 2d\vec{r}\hat{\varepsilon}d\vec{r}$. The strain tensor $\varepsilon_{jk} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_k} + \frac{\partial u_k}{\partial x_j} + \frac{\partial u_j}{\partial x_k}\frac{\partial u_k}{\partial x_j}\right)$ – is a symmetric tensor that, when going over to the theory of linear deformations, is rewritten in the form: $\varepsilon_{jk} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_k} + \frac{\partial u_k}{\partial x_j}\right)$. It can be divided into two parts, characterizing the volumetric and shear deformation: $\varepsilon_{jk} = \frac{1}{3}\varepsilon ll\delta_{jk} + \left(\varepsilon_{jk} - \frac{1}{3}\varepsilon ll\delta_{jk}\right)$. The components of the strain tensor have no dimension.

The stress tensor, which characterizes the "strength" characteristics of the deformation of a rigid body, is determined by an expression $f_j = \sigma_{jk} n_k$, that makes sense if we consider within the body the allocated volume, to which force $\vec{F}_{(in)} = \oint\int \hat{\sigma} d\vec{s} = \iiint div\hat{\sigma} dv$ and moment $\vec{M}_{(in)} = \oint\int [\vec{r}, \hat{\sigma} d\vec{s}] = \iiint [\vec{r}, div\hat{\sigma}] dv$ "acts", the same expressions are valid for the whole body. The components of the stress tensor have the dimensionality of pressure [14, 15].

When considering the linear theory of elasticity, the tensors of stresses and deformations are connected by means of a fourth-order tensor: $\sigma_{\mathrm{jk}} = \lambda_{\mathrm{jklm}} \varepsilon_{\mathrm{lm}}$, all properties of which will not be described here. The tensor λ_{jklm} characterizes the elastic properties of matter and, in the most general case, has 21 independent components of 14. The elastic properties of isotropic substances are described by two independent components (6 for orthotropic substances). Naturally, the tensor λ_{jklm} itself can be a function of the coordinates if the substance is inhomogeneous. The components of the tensor λ_{jklm} have the dimension of pressure.

In many technical calculations, the elastic properties of substances are characterized by the Young's modulus E and the Poisson's ratio μ, they completely describe the elastic properties of an isotropic substance with linear elasticity, they are used for finite element calculations of technical structures. For problems with nonlinear elasticity characteristics, the quantities E and μ can be introduced as functions that depend on the local values of the strain tensor $\varepsilon_{\mathrm{jk}}$. The Young's modulus of elasticity E has the dimension of pressure, and the Poisson's ratio μ is a dimensionless quantity. The deformed state of a rigid body is described by an equation connecting the stress tensor $\hat{\sigma}$ with the "external" forces $\vec{f}$ acting on the body and the acceleration of its individual points: $div\hat{\sigma} + \vec{f} = \rho\vec{a}$.

The application of methods for describing the motion of an absolutely elastic body to solids with finite values of elastic modules has an approximate nature.

For a complete description of the rigid body state, it is necessary to twice integrate the equation $div\hat{\sigma}(\vec{r}) + \vec{f}(\vec{r}) = \rho(\vec{r})\vec{a}(\vec{r})$ in which each of quantities is a coordinate function of the point $\vec{\mathrm{r}}$ – 3 of scalar quantities. If it is impossible to use any simplifying assumptions in the problem, then the order of the system is formally equal to infinity. Naturally, such problems in some cases allow an analytical description, but in practice this happens very rarely, and analytical methods are used only as approximate descriptions and approximations.

Classical calculation methods allow solving problems only with significant idealization, replacing the actual construction with its design scheme. The introduction of computer systems into engineering practice allows, using numerical methods, to perform calculations of almost any complex structure, breaking it into finite elements.

Standard engineering structures can be considered as combinations of structural elements connected by a discrete number of nodes. If the "force-displacement" relation is known for individual elements, then using the well-known techniques for calculating structures, one can obtain properties and study the behavior of the combined structure.

Many complex theoretical problems of the railway track could not be solved in the past due to the lack of appropriate computer technology and software. Today, this technique can be effectively used to solve urgent problems of track economy. New materials, new machines and technological processes and a new strategy for servicing the railway track affect its design and its characteristics.

It is advisable to begin the search for a constructive solution with the creation of a mathematical model and its analysis. The creation of the mathematical model is preceded by a comprehensive analysis of the behavior of the railway track during operation, the collection of load test characteristics, physical modeling of operational situations. The long-term work of the railways scientists of a number of countries has led to the establishment of important properties and elements characteristics of the force-displacement path that are necessary for preliminary assessment of the possible changes range in the initial data. Considerations of a qualitative nature are taken into account additionally and kind of "background" for mathematical modeling.

The models give an approximate mathematical description of the processes occurring in the railway track construction as a whole, or in the work of its individual elements.

Models contain the target optimized function and some set of constraints. Varying variables, objective functions and constraints constitute a mathematical optimization problem.

In physical modeling, it is usually possible to take into account only the main factors, and the influence of the unaccounted "background" should be checked when testing new path designs. The test system usually includes experimental research, operation on the experimental track sections of a number of railways, and then, after completion and sufficient testing, new technical solutions are fixed by standards for temporary and permanent use on the railways network. But the beginning of this complex path should not be the manufacture of an experimental design from drawings (the use of the trial and error method), but the study of new path design models or a new element in order to find and justify the parameters of reliable structural elements. Only when this is done, it is possible to manufacture prototypes for their further testing.

Recently, new mathematical models have been developed that describe a virtual prototype of the path design. They contain all of its elements, taking into account their technical condition. These models can describe a worn path or path with separate deviations from specifications [16-19].

In models as elements there are:

-rails;

- all elements of intermediate rail fastenings, namely: linings and gaskets, metal sub-rail pads with flanges, terminals of intermediate rail fasteners, mortgages and anchor bolts, nuts and washers;
- reinforced concrete sleepers with reinforcement, washers;
- crushed ballast prism;

-sand cushions, various options for reinforcing the ballast prism and earthen cloth with nets, carpets of non-woven materials, plates of expanded polystyrene.

Elements of the path in models have strictly corresponding to the actual geometric dimensions and physical properties.

EXPERIMENTAL PART. The use of the finite element method (FEM) for path constructions calculating. When calculating designs by this method, instead of the traditional design scheme, a precise geometric description of the structure is made, for which the following model objects are created: "points" (PT), "curves" and "lines" (CR), "contours" (CT), "surfaces" (SF) and "regions" (CP), "volumetric bodies" (VL, PH, PA). The types of finite elements that characterize their constants and physico-mechanical properties are declared. A finite element mesh can be created manually or with a parametric or automatic "splitting" of geometric objects, boundary conditions and loads can be declared for individual grid elements and for groups of elements associated with geometric objects. The design is calculated (in static, dynamics, oscillations, evaluation of the development of cracks, optimization of parameters, etc.). The results of calculations can be presented in the form of data lists, graphs, color diagrams and figures, "deformed species" or animation of the calculated processes (Figure 4).

The solution of linear static problems reduces to the solution of the matrix equation:

$$[\mathrm{R}]\{\mathrm{U}\}=\{\mathrm{F}\},$$

where [R] is the square stiffness matrix; {U} is the vector of unknown node displacements; {F} is the vector of external influences.

The decision

$$\{\mathrm{U}\}=[\mathrm{R}]^{-1}\{\mathrm{F}\},$$

reduces to the inversion of the rigidity matrix [R].

The load of a railway track by a moving rolling stock is a random process, depending on its design and parameters, axial loads, speed of movement, deformations of the path under load, irregularities on rails and wheels, dynamic qualities of rolling stock, variability of stiffness and dissipation characteristics, stresses, etc.

To ensure a complete similarity of the model in-kind, compliance with: geometric, mechanical, kinematic and dynamic similarity of the model in kind is required.

The difficulties of physical modeling usually consist in the impossibility of meeting the contradictory requirements of the determining similarity criteria while reducing the linear dimensions of the model. The search for self-similarity zones and domains of applicability of the equations makes it possible to partially solve these problems. When using "virtual prototypes" of models on a computer, there are no problems with linear dimensions and properties of materials.

The finite element model of the railway track is shown in figures 1 and 2.

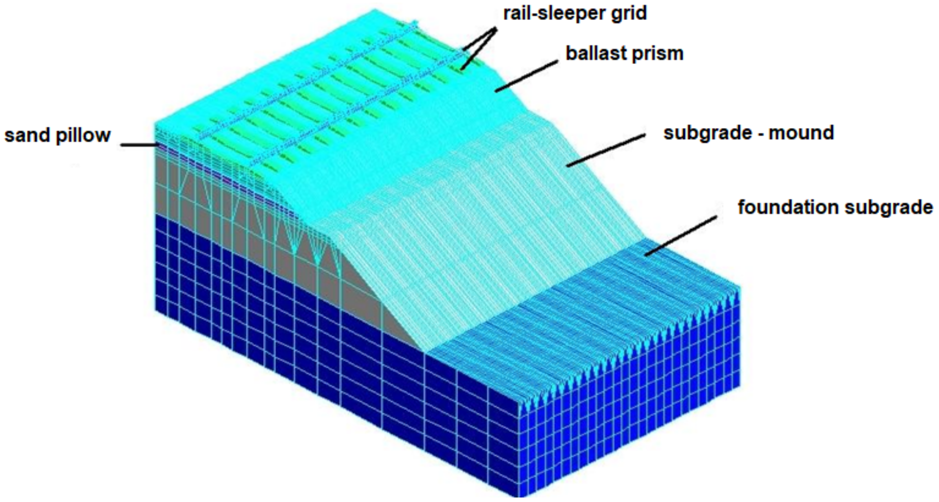

Figure 1 – Axisymmetric finite element model of the railway track section (double-track line)

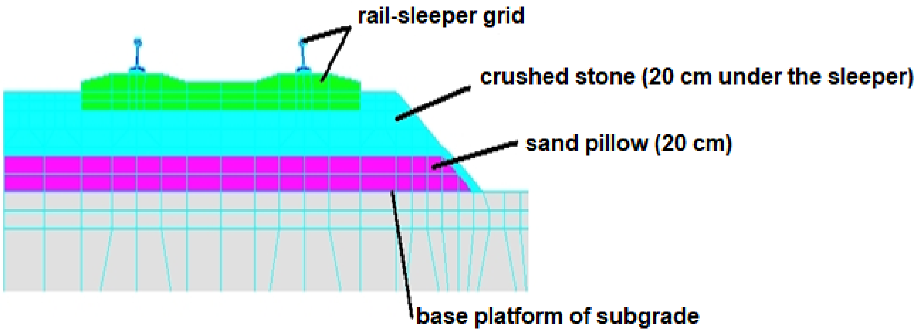

Figure 2 – Fragment of the axisymmetric finite element model of the railway track
(contact zone of the upper track structure and the roadbed top)

The above technique can be used for calculating the roadbed on a weak base and in the presence of karst cavities in the bottom of the embankment. The applicability of numerical calculations methods to the assessment of the stress-strain state of ground embankment is substantiated by numerous works of academician NAS of Kazakhstan Sh. M. Aitaliyev and his students [4].

Calculation of the stress-strain grounds state of two-layer embankments spilled from the grounds of the Southern region of Kazakhstan. Most of the time, the stresses in the ground embankment are determined by the intrinsic weight of the ground. On the axis of the embankment, they are equal to the hydrostatic pressure:

$$\sigma = \gamma \cdot h, t/m^2,$$

where γ – specific gravity of ground, t/m^3; h – distance from the top of the roadbed, m.

The train load causes the greatest additional stresses on the main area of the roadbed under the sleeper. With the removal down from the main site, these additional stresses decrease because of the spread to an ever larger area. Where σ- the stress component of the train load becomes less than $\sigma > 0,1 \odot h\gamma$ of hydrostatic pressure, the lower boundary of the working zone of the subgrade is located.

Consider the application of the numerical calculation method for the stress-strain state of a railway embankment using the example of a two-layer embankment on a solid foundation on a straight track. The characteristics of the two types of ground used for mound filling are given in table.

Calculation characteristics of a two-layer embankment ground

Characteristics of the ground layer	Modulus of deformation E, MPa	Poisson's ratio	Specific gravity, t/m^3
1st layer	16,0	0,25	1,7
2nd layer	5,0	0,30	1,75

The developed finite-element model of a two-layer embankment (cross-section) is shown in figures 3 and 4.

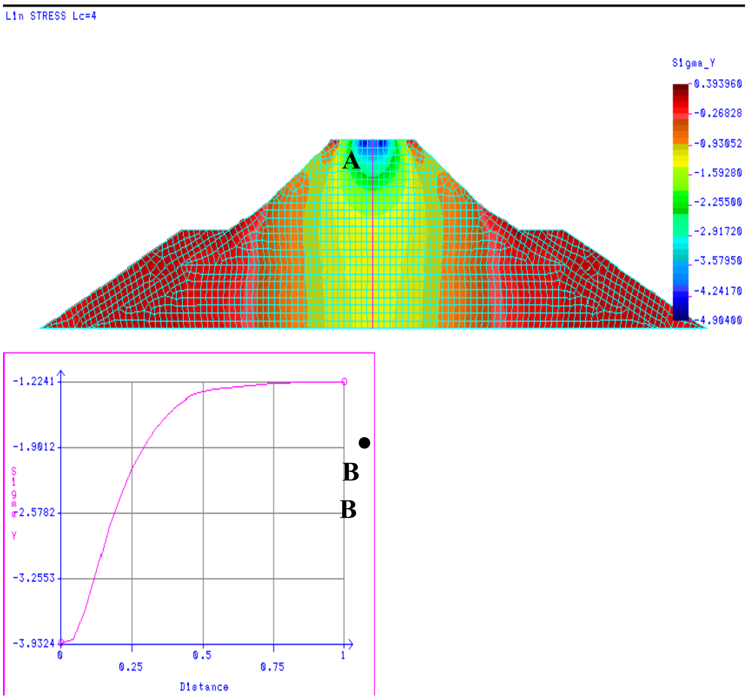

Figure 3 – Distribution of vertical stresses in the grounds embankmentfrom the train load at the device of berms.
Line A-B – vertical along the axis of the embankment

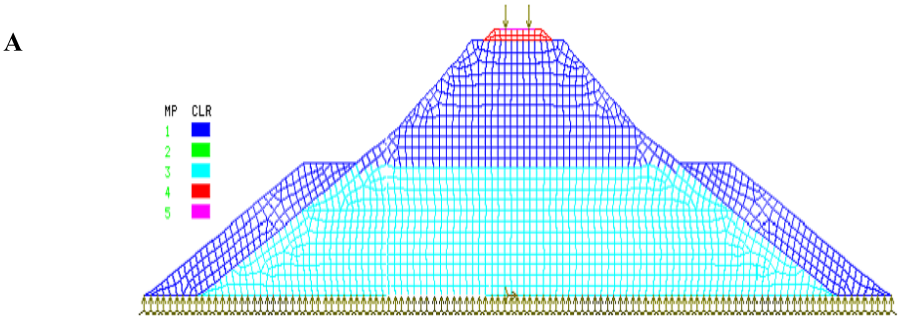

Figure 4 – Embankment variant with the device of two berms

Calculations are performed using the FEM method for distributing vertical stresses and complete displacements of the embankment grounds under a train load of 10 tf per running meter of railway track.

As the calculations have shown, the lower - less durable layer of the ground has the characteristic deformation of the spreading of the embankment (this can be seen on the vector plot of ground movement under load (figure 5). Despite the small absolute values of spreading slopes from a single loading, the rheological nature of the lower ground layer will lead to the need for straightening of the path lifting on rubble, which is associated with the costs and restrictions of the speed of the movement of trains.Structural measures are necessary to prevent such deformations of the ground embankment, for otherwise It is a long time in the operation of the path will have to lead the way on, lifting of the ballast and to limit the speed of the large local subsidence way.

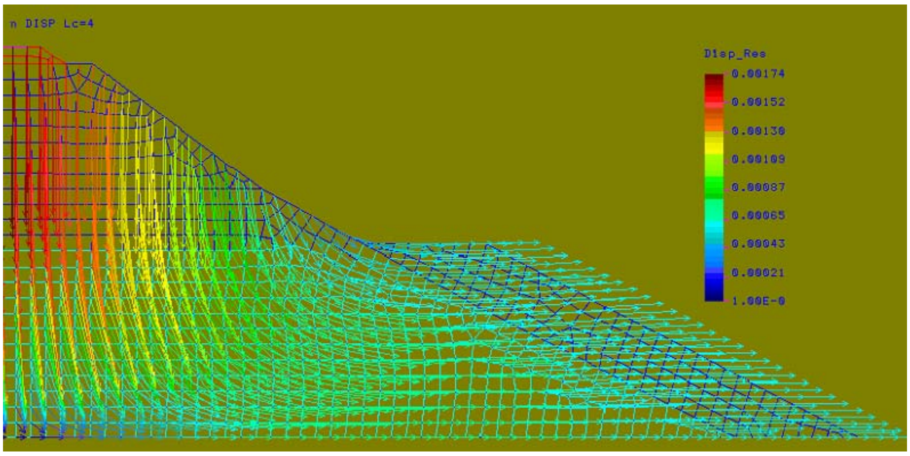

Figure 5 – Vector plot of mound deformations with the berms device

Considering two variants of embankment reinforcement: a 6 m high berm device and a "wall in the ground" device on the width of the main site of the roadbed in weaker ground (figure 6). We will perform calculations of these variants and compare the new data with the initial calculation.

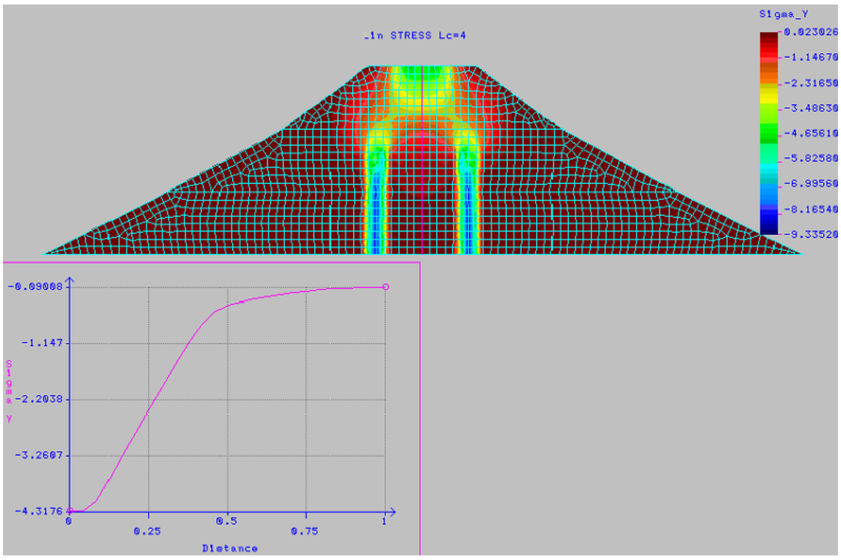

Figure 6 – Distribution of vertical stresses in the ground embankment from the train load when the wall is installed in the ground. Line A-B - vertical along the axis of the embankment

After installation of a double-sided berm 4m wide on rubble top, delivered by train, the transverse movements of the weak lower layer of the embankment decreased slightly. Vertical sediments from the train load exceed the deformations of the variant with the "wall in the ground" device. According to the calculation (figure 6) in the version of the device "walls in the ground", the sprawl of the ground in the projection of the main site of the embankment ceased (figure 7).

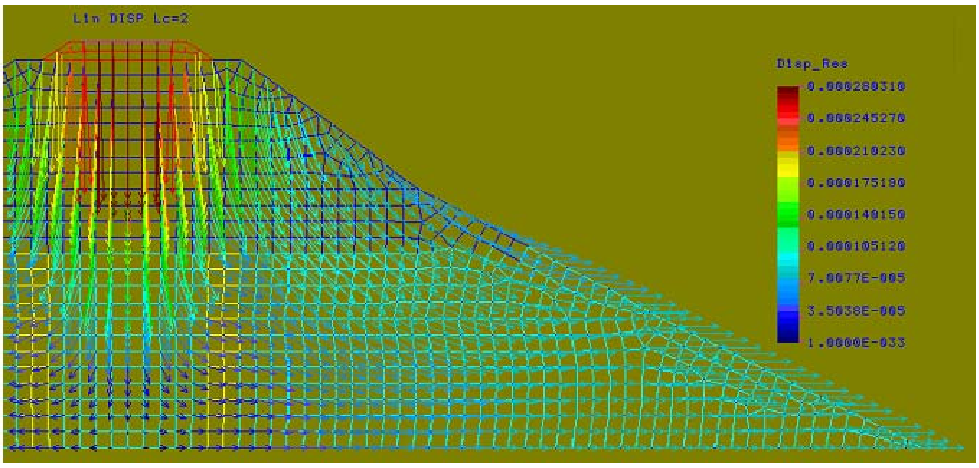

Figure 7 – Vector graph of mound deformations with the construction of a wall in the ground

The total elastic sediment of the embankment became smaller than in the version of the bilaterial berm apparatus. The mound stabilizes only when the width of the berm is 8 m.

Conclusion.

1. Appearance on the newly constructed railway sections of the "diseased roadbed" except for the violation of the technology of work is caused by the excessive use of standard designs, inaccuracy of the initial design data of the roadbed and the imperfection of traditional calculation methods, in which the ground embankments is considered as one-dimensionally deformable isotropic material under train load.

2. In cases where heterogeneous grounds are used for erecting a roadbed, it is recommended to check their stress-strain state under the train load by numerical methods.

3. It is recommended to use the finite-element virtual path model developed by us for calculating the stress-strain state of a layered embankment, including the upper structure and the earthen cloth.

4. To evaluate the possible plastic deformation of a less durable ground layer in the embankment ("creep in the mound"), it is recommended to calculate a vector plot of the ground displacement of the embankment under the train load. If the tangential stresses from the load exceed the permissible ground stresses, the lines of ground particles movement will noticeably deviate from the vertical and this is an indication of the need to reinforce the layered embankment.

5. Comparison of options for possible design solutions for the stabilization of layered embankments should be carried out according to their technical and economic indicators, while the characteristics of the stressed-deformed ground state in the embankments variants are equal.

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ЖАЛПЫ ТЕМІР ЖОЛ КОНСТРУКЦИЯСЫНДА НЕМЕСЕ ОНЫҢ ЖЕКЕЛЕГЕН ЭЛЕМЕНТТЕРІНІҢ ЖҰМЫСЫНДА БОЛЫП ЖАТҚАН ПРОЦЕСТЕРДІ СИПАТТАЙТЫН МАТЕМАТИКАЛЫҚ ҮЛГІЛЕРДІ ӘЗІРЛЕУ

Аннотация. Мақалада жалпы темір жол конструкциясында немесе оның жекелеген элементтерінің жұмысында болып жатқан процестерді сипаттайтын математикалық модельдерді әзірлеуге арналған. Қазақстанның оңтүстік аймағының топырақтарынан төгілген екі қабатты үйінділер топырағының кернеулі-деформацияланған жай-күйін есептеу мысалы келтірілген.

Түйін сөздер: топырақ, үйінді, темір жол, жер төсемі, ығыстыру.

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РАЗРАБОТКА МАТЕМАТИЧЕСКИХ МОДЕЛЕЙ, ОПИСЫВАЮЩИХ ПРОЦЕССЫ, ПРОИСХОДЯЩИЕ В КОНСТРУКЦИИ ЖЕЛЕЗНОДОРОЖНОГО ПУТИ В ЦЕЛОМ, ИЛИ В РАБОТЕ ЕГО ОТДЕЛЬНЫХ ЭЛЕМЕНТОВ

Аннотация. Статья посвящена разработке математических моделей, описывающих процессы, происходящие в конструкции железнодорожного пути в целом, или в работе его отдельных элементов. Приведен пример расчета напряженно-деформированного состояния грунта двухслойных насыпей, отсыпанных из грунтов Южного региона Казахстана.

Ключевые слова: грунт, насыпь, железнодорожный путь, земляное полотно, сдвиг.

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